

ExoMars/TGO Science Orbit Design

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This paper describes the development of the science orbit for the 2016 ESA/NASA collaborative ExoMars/Trace Gas Orbiter (TGO) mission. The initial requirements for the ExoMars/TGO mission simply described the science orbit as circular with a 400 km altitude and a 74 deg inclination. Over the past year, the JPL mission design team worked with the TGO science teams to refine the science orbit requirements and recommend an orbit that would be operationally feasible, easy to maintain, and most important allow the science teams to best meet their objectives.

1.0 Introduction

The 2016 ESA/NASA collaborative ExoMars/Trace Gas Orbiter mission was to consist of an ESA Trace Gas Orbiter (TGO), with a science payload including NASA-funded instruments and an ESA Experimental Descent Module (EDM) launched on an Atlas V rocket. NASA recently decided to cancel their participation in this mission due to budget constraints so ESA has partnered with the Russian Federal Space Agency and is continuing as planned. This paper describes the original ESA/NASA mission and the development of the science orbit based on inputs from the original ESA/NASA science instrument teams. The ESA/RFSa collaborative mission would have a different suite of science instruments than those described in this paper. However, the science orbit design described here could be beneficial to future Mars missions focused on trace gas detection.

The mission was to launch in January 2016 and take approximately 9 months to arrive at Mars. Three days prior to arrival, the ESA EDM would be released from the TGO and land on the surface of Mars. The TGO spacecraft would then do an orbit insertion burn to capture into a 4-sol orbit followed by a series of maneuvers to target the desired inclination and reduce the apoapsis to a 1-sol orbit. The spacecraft would spend the next 6 to 9 months aerobraking to further reduce the orbit altitude. The end of aerobraking would occur before solar conjunction and would conclude with a series of maneuvers that target the desired science orbit. The science phase would begin in May 2017 and last for one Martian year. The science phase would be followed by the relay phase that would cover the 2018 landing mission as well as continue science observations.

The TGO spacecraft per the original ESA/NASA arrangement is shown below in Figure 1. The TGO spacecraft is a Thales Alenia Space (TAS) design derived from its highly successful SpaceBus line of communications satellites. The spacecraft mass is 4330 kg at launch, including the EDM. The orbiter is a 3-axis controlled design with a hydrazine and oxidizer propulsion system including a single 400N engine and twenty 10 N ACS thrusters. For fine pointing, the orbiter uses 20 N-m-s reactions wheels. The two solar arrays are single axis controlled and are kept Sun pointed most of the time. A 2.2 m high gain antenna (HGA) is 2 axes controlled and is kept Earth pointed

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most of the time, providing high rate X-band science data return. The spacecraft is oriented with its $-Y$ -axis nadir pointed and its $-X$ -axis Sun pointed nearly continuously. The science instruments are mounted on the $-Y$ face of the orbiter. Because the $-X$ -axis is Sun pointed, the nadir oriented science instruments are gimballed to align boresights for ground track observations. The solar occultation instruments are mounted such that they point near the limb when the orbiter is nadir pointed and the orbiter needs to slew only a few degrees for the instruments to observe the occultations. A UHF radio system is used to provide communications with landers and rovers on the surface of Mars. The low gain omni-directional antenna is mounted on the nadir deck ($-Y$) to allow relay links whenever a lander or rover are in view.

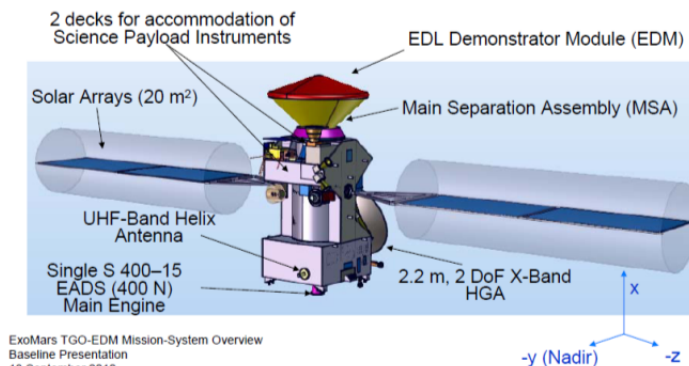


Figure 1: TGO Spacecraft

The broad science themes of the 2016 Trace Gas Orbiter mission included [1]:

1. Detect a broad suite of atmospheric trace gases and key isotopes;
2. Characterize the spatial and temporal variation of methane and other key species, ideally representing families of photochemically important trace gases (HOx , NOx , hydrocarbons, etc.) and their source molecules (e.g. H_2O);
3. Localize the sources and derive the evolution of methane and other key species and their possible interactions, including interactions with atmospheric aerosols and how they are affected by the atmospheric state (temperature and distribution of major source gases; e.g. water); and
4. Image surface features possibly related to trace gas sources and sinks

The science orbit design was a collaborative effort between the mission design team and the science instrument teams. The final design was agreed upon by all teams and is described in detail below.

The TGO science instruments included:

- MATMOS – Mars Atmosphere Trace Molecule Occultation Spectrometer
- NOMAD – Nadir and Occultation for Mars Discovery
- MAGIE – Mars Atmospheric Global Imaging Experiment
- EMCS – ExoMars Climate Sounder
- HiSCI – High-resolution Stereo Color Imager

2.0 Inclination Trade Space

The first step in the science orbit design process was to determine the optimal orbit inclination for the science instruments. The mission proposal specified a 74 deg inclination with a range of ± 10 deg based on an initial estimate from the NASA Project Scientist. The science teams wanted to analyze the inclination trade space of 74 deg ± 10 deg, in 1 deg steps in order to find an optimal inclination for all the teams. The main criterion for the science teams was to get 4 to 6 Time-Of-Day (TOD) cycles per Mars year and good global distribution for solar occultation observations, particularly at the poles and the equator. A TOD cycle is the amount of time required for the orbit plane to rotate about the Mars pole back to the same local solar time. Criteria for individual science team investigations were also considered and included in the evaluation of overall orbit inclination trade study.

Occultation observations are the primary orbit design driver for this mission. The occultation observations occur when the spacecraft enters or exits eclipse and the atmosphere occults the Sun. The science measurements would be taken in the direction of the Sun, looking through the Martian atmosphere from the surface up to 200 km altitude with respect to the tangent point of Mars along the sun line. The occultation geometry is shown below in Figure 2.

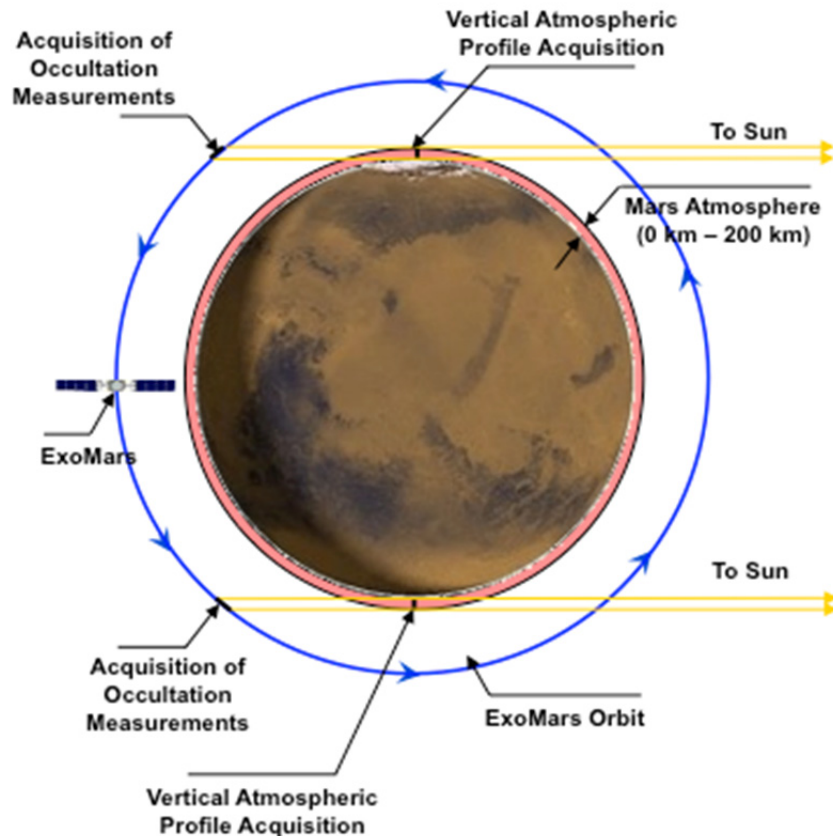


Figure 2: Limb Occultation Geometry (altitudes not to scale)

For each of the 21 inclination options in this trade space study, a two-year trajectory file was developed using an element of the JPL mission design software MONTE called “Morbiter”. These 21 Morbiter trajectories are based on mean element propagation using a 33x33 degree and order Mars gravity field. These reference trajectories did not include third body effects, atmospheric drag, or solar radiation pressure. The two-year trajectory files used a 400 km mean altitude as well as a frozen eccentricity and argument of periapsis. The 400 km mean altitude was used based on the proposed ESA requirements. ESA did not specify frozen orbit conditions in their requirements; but, the science team agreed to use them in this study.

The benefit of a frozen orbit is to provide the most circular orbit achievable at low Mars altitudes, thus, simplifying operations and planning activities for the TGO mission. The frozen orbit altitude variation between periapsis and apoapsis would only be about 65-70 km. Also, frozen orbits have a variation of only a few kilometers in altitude at specific latitudes compared to up to 170 km altitude variation for the other orbit types[2]. A plot of altitude versus latitude for the TGO frozen orbit reference trajectory is shown below in Figure 10 of Section 4.

For each of the 21 trajectory files, a series of plots were generated to assist the science teams in their selection. The tangential latitude versus time plots and the Beta Angle versus time plots were used to analyze the TOD cycles per Mars year. The solar longitude (Ls) is also included in the Beta Angle plots and is defined as the Mars-Sun angle measured from the Northern Hemisphere spring equinox where Ls=0deg. Ls is independent of orbit inclination and therefore the same for all inclination options. The Beta Angle is defined as the angle measured between the Sun vector and the orbital plane and does differ for each inclination option.

Examples of these plots for the 64 deg, 74 deg, and 84 deg inclinations are shown below in Figures 3, 4 and 5. The time from one peak to the next in the Beta Angle plots below represents one TOD cycle. Similarly, a set of two lobes in the tangential latitude plot represents one TOD cycle. The plots show that the lower inclinations have faster TOD cycles but not as much polar coverage.

The MATMOS instrument had limits on processing occultation durations greater than 450 seconds; so, the data points are color coded with blue representing occultations <450 seconds between 200 km and 0 km altitude. The NOMAD instrument could process longer duration occultations; so, red represents occultation durations >450

seconds between 200 km and 0 km. Both instrument teams were interesting in grazing occultations, shown in black, in which the tangent point never reaches down to 0 km.

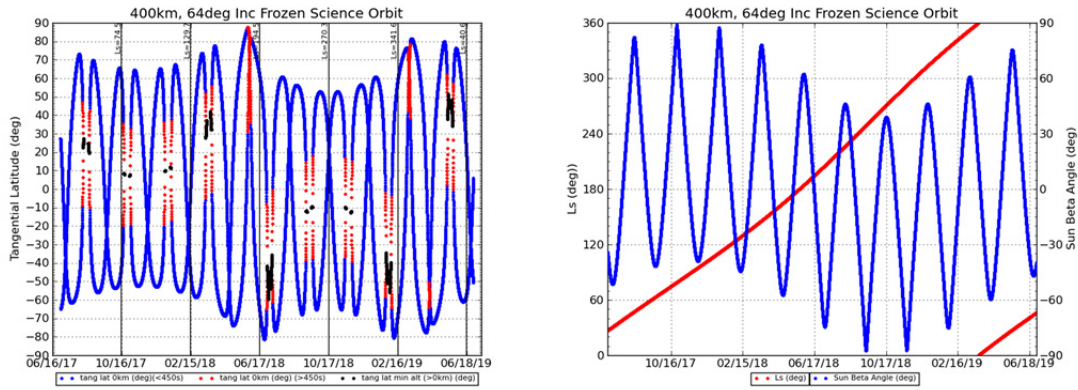


Figure 3: Tangential Latitude (left graph), Ls (red) and Beta Angle (blue) (right graph) for 64 deg Inclination Reference Orbit

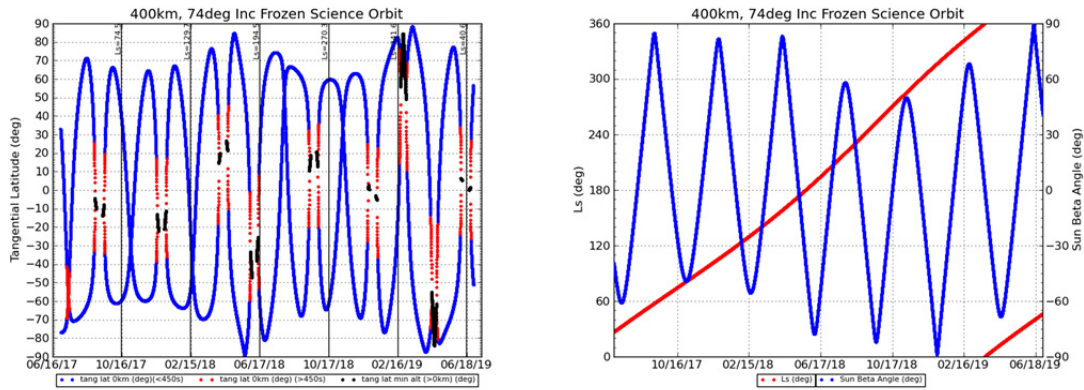


Figure 4: Tangential Latitude (left graph), Ls (red) and Beta Angle (blue) (right graph) for 74 deg Inclination Reference Orbit

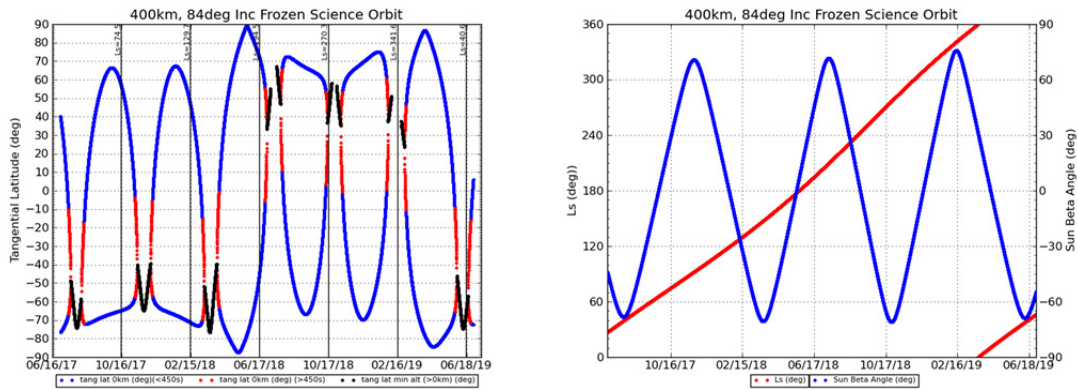


Figure 5: Tangential Latitude (left graph), Ls (red) and Beta Angle (blue) (right graph) for 84 deg Inclination Reference Orbit

Other associated data that the science teams were interested in included: projected ground distance of tangent point verses time, occultation durations verses time, statistics on ground distance (delta latitude/delta longitude verses time and verses distance), statistics on tangential latitude (# of latitude crossings, time intervals between crossings, total number of occultations), and orbital elements (altitude, eccentricity verses argument of periapsis, right ascension of ascending node).

Each of the science instrument teams evaluated the trajectories, the plots and the other associated data. They presented their evaluations at the March 2011 Orbiter Science Working Team meeting. In summary, their conclusions are as follows:

- The EMCS team noted that an inclination greater than 64 deg is required to ensure polar coverage. They preferred 4-6 TOD cycles per Mars year that requires inclinations of 81.2 deg to 75.3 deg.
- The HiSCI team preferred 79 deg inclination or higher which would provide them viewing opportunities of polar dune fields, outliers, and layered deposits and scarp retreats. They noted that rolling the spacecraft could be an option to get the viewing opportunities if a lower inclination were selected.
- The MAGIE team liked the 74 to 84 deg inclinations because they provided full coverage of the planet with 1-2 km resolution at the poles. They would have been happy with any inclination greater than 71 deg.
- The MATMOS team preferred a 69 deg inclination. They wanted both sunrise and sunset occultations and they preferred the occultation info as close in time as possible, meaning they wanted fast repeating TOD cycles. Also, they noted that in the Northern summer the 69 deg inclination would give the most North Pole coverage.
- The NOMAD team preferred a 76 deg inclination. For their team, it was important to get polar coverage.

At the end of the March 2011 Orbiter Science Working Team (OSWT) meeting, the science instrument teams came to a consensus to stay with the originally proposed 74 deg inclination.

3.0 Ground Track Pattern

The initial requirements for the science orbit are described in the ESA Consolidated Report on Mission Analysis document [1]. The document describes the science orbit as circular with a 74 deg inclination and a mean altitude between 350 and 420 km. The document also states that the orbit should have repeating groundtracks with a time frame between 3 to 5 sols.

After the OSWT selected the 74 deg orbit inclination, they expressed an interest in refining the ESA orbit altitude requirements and establish a ground track repeat pattern beneficial to all science teams. The OSWT initially provided the following two constraints for this analysis:

- Altitude trade space of 360 km to 462 km
- Ground track spacing should be less than 8 km apart at the equator over a long period of time. The 8 km constraint was based on the HiSCI cross-track footprint.

The following equation determines approximately how many orbits it would take to achieve equally spaced ground track spacing at the equator [3]:

$$(1) \quad \text{Distance between equally spaced groundtracks} = \text{Mars Circumference} / \text{Number of Orbits (R)}$$

It will take approximately 2600 orbits (approximately 212 sols) to achieve 8 km ground track spacing at the equator. There are hundreds of orbit options that can achieve the required long-term ground track spacing within the altitude constraints provided but the order in which each one builds up the groundtrack spacing at the equator varies. The parameter Q can be used to reflect how the groundtracks fill in the gaps between successive orbits.

$$(2) \quad Q = \text{orbits to exact repeat (R)} / \text{sols to exact repeat (D)}$$

The groundtrack will begin to repeat after D sols and the orbit R+1 will be identical to orbit 1. The orbit options that meet the altitude constraints and have long-term ground track spacing within a range of 7.5 km to 8.15 km result in Q values between 12.275 to 12.52. Figure 6 shows the orbit altitude verses Q value for all the orbit options.

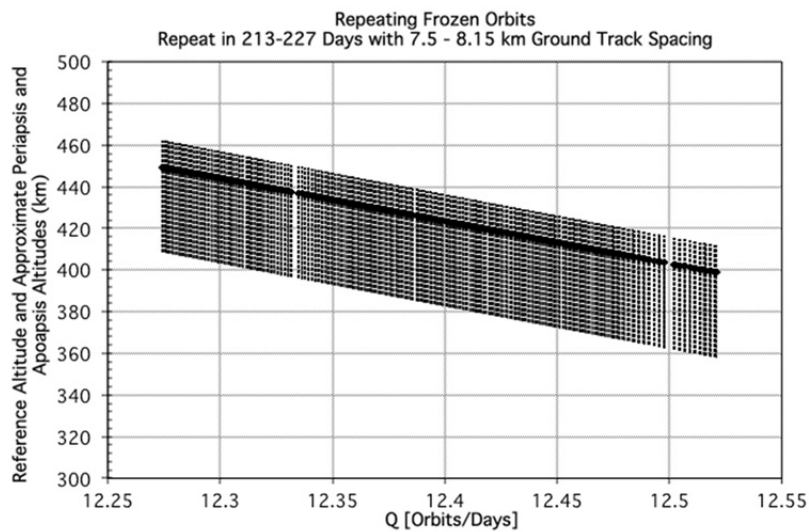


Figure 6: Orbit Altitude verses Q

To further refine the orbit options, the OSWT provided the following mid-term and short-term ground track spacing constraints:

- Mid term: 16 km ground track spacing after approximately 100-120 sols (~1400 orbits)
- Short term:
 - 1760 km ground track spacing after one orbit (orbit 2)
 - 880 km ground track spacing after one sol (orbit 13)
 - 440 km ground track spacing after three sols (orbit 39)

The short-term constraint of 440 km spacing after three sols (orbit 39) was not feasible based on the altitude constraints. In order to meet this 440 km spacing constraint, an orbit altitude of 467 km would be required which exceeds the maximum of 462 km. However, an alternate solution was found within the altitude constraints that achieves approximately 343 km even ground track spacing after four sols (Orbit 51) and the OSWT approved. The other two short-term constraints of 880 km spacing after one sols and 1760 km spacing after one orbit were easily met.

The Q values that achieve these three short-term constraints ranged from 12.395 to 12.405. Orbits with Q values closer to integer numbers have groundtracks which lie nearly on top of the groundtracks of the previous repeat cycle, whereas orbits with more fractional Q values have groundtracks that have shifted left or right of the previous cycle's groundtracks by the fractional part of the Q value [2]. Therefore, the orbits with Q values of 12.400 are exact repeat orbits and would not meet the mid term or long term ground track spacing requirements. The orbits with Q values of 12.395 and 12.405 have groundtracks that shift to the right or left by 7.5 km. A Q value of 12.405 was selected for a reference.

Based on the selected Q value, the mid-term constraint of 16 km spacing could only be achieved after 185 sols instead of after 100-120 sols (1400 orbits). Different Q values within the original 12.275 to 12.52 trade space could have achieved the mid-term constraint; but it would mean giving up the short-term constraints of even spacing at 343 km after four sols. The science team agreed to maintain the short-term constraints and update the mid-term constraint to 16 km spacing within 185 sols. For a Q value of 12.405, the ground track pattern slowly builds up global coverage at the equator by closing the gap at a rate of 7.5 km every 459 orbits. The ground track repeats after 2816 orbits (227 sols) and the spacing at the equator is 7.5 km **meeting** the long-term constraint. The short term, mid term, and long term ground track patterns are shown below in Figures 7, 8, and 9.

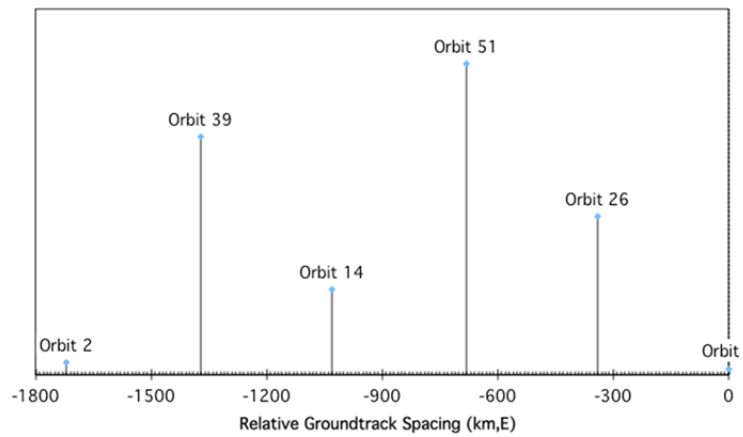


Figure 7: Short Term Ground Track Pattern at the Equator

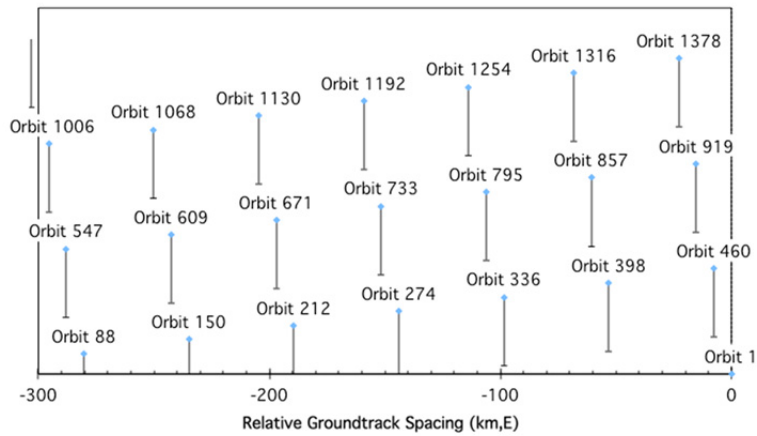


Figure 8: Mid Term Ground Track Pattern at the Equator

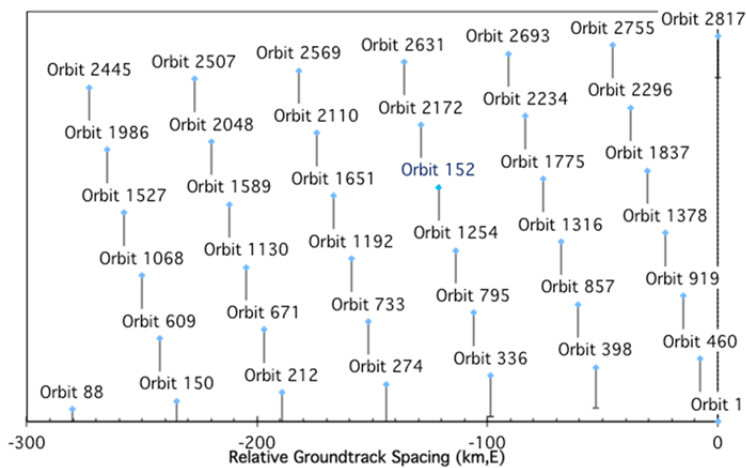


Figure 9: Long Term Ground Track Pattern at the Equator

4.0 Reference Orbit Parameters

A reference orbit that matches the desired ground track patterns was developed with the Morbiter software. The orbital elements are shown in Table 1. This reference trajectory has a mean periapsis altitude of 381 km and a mean apoapsis altitude of 437 km as shown in the Altitude versus Latitude plot in Figure 10 below. Figure 11 shows the mean inclination value is 74.0405 deg based on the previous inclination trade study. Figure 12 shows that the eccentricity and argument of periapsis are frozen.

Table 1: Orbital Elements for Science Reference Trajectory
(IAU Mars Fixed frame at Epoch of 30-JUN-2017 09:15:01 ET)

	Mean Elements	Osculating Elements
Semimajor Axis	3787.5237 km	3779.2715 km
Eccentricity	0.0068	0.0040
Inclination	74.0405 deg	74.0090 deg
Argument of Periapsis	269.2147 deg	267.8467 deg
Right Ascension of Ascending Node (RAAN)	-158.9599 deg	-158.9690 deg
Mean Anomaly	0 deg	1.1374 deg

Figure 13 shows the right ascension of the ascending node for the reference trajectory. The selection of a 74 deg inclination leads to a node regression rate of 2.817 deg/day. The groundtracks would, therefore rotate through a full local solar time cycle of 0 to 24 hours approximately every 128 days (one TOD cycle). The HiSCI team may want to re-examine their mapping strategy considering that some groundtracks would be in darkness.

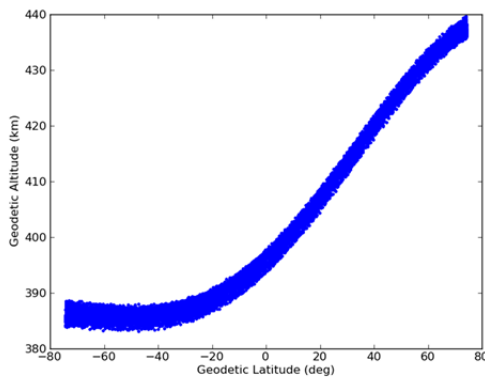


Figure 10: Reference Orbit Altitude vs Latitude

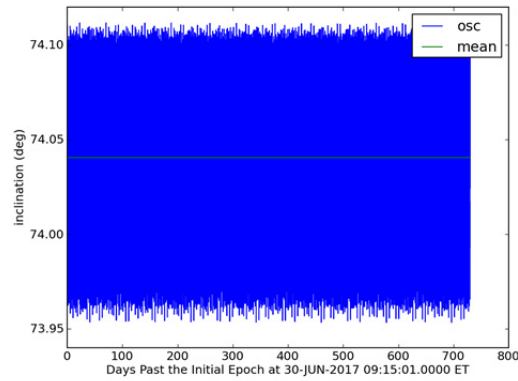


Figure 11: Reference Orbit Inclination

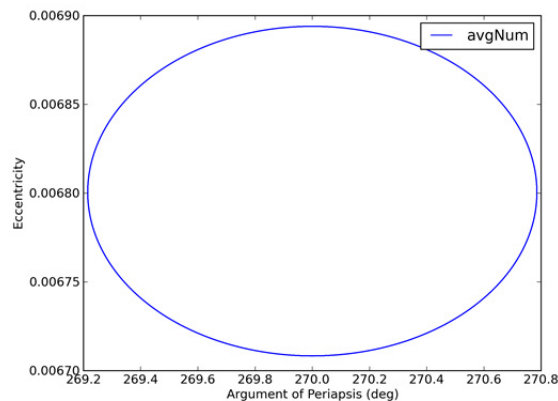


Figure 12: Mean Eccentricity versus Argument of Periapsis

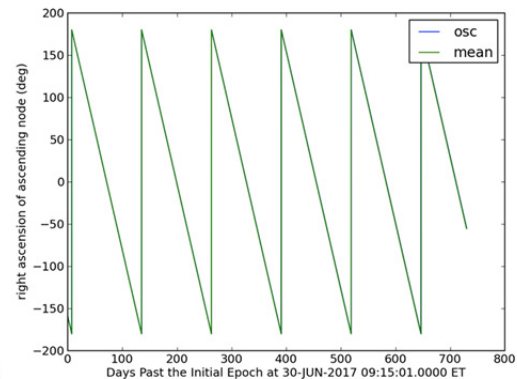


Figure 13: Reference Orbit RAAN

5.0 Orbit Maintenance Strategy and Delta-V budget

The next step in the design process was to develop an orbit maintenance strategy taking into account the effects of all possible orbit perturbations such as atmospheric drag, reaction wheel unloading, solar pressure, and maneuver execution errors. ESA had stated that their strategy was to do monthly maneuvers to correct back to a pre-determined reference trajectory. A more detailed strategy was required in order to maintain the reference trajectory and ground track pattern described above.

At the time of writing this paper, ESA had done a preliminary analysis on the Delta-V effects from off loading torque. ESA estimated one desat would be required every six orbits. According to the analysis, the along-track component of the Delta-V effects from a desat could be as much as a few mm/s, depending on the orbit beta angle. To minimize the desat effects to the orbit, several options were noted. Three such options included: 1) schedule the desat to occur at a place in the orbit where there would be a zero along-track component, 2) split a desat into two parts such that one has a positive along-track component and the other has a negative along-track component, resulting in a near zero Delta-V effect, or 3) minimize the desat propellant usage by selecting an optimal orbit location. All options are reliant on good orbit predictability for planning purposes that may be difficult to achieve. Further analysis would be required to determine the best desat strategy.

The JPL mission design team did a preliminary orbit trim maneuver (OTM) analysis that did not include any effects from the desats mentioned above. The following assumptions were used: an average orbit altitude of 415 km, atmospheric density of 3.155×10^{-6} kg/km³ based on the average altitude during the TGO primary science phase, a drag coefficient (Cd) of 2.0, a spacecraft area of 32.5 m², and a spacecraft mass of 1580 kg. The results showed that to stay within ± 4 km of the ground track pattern (i.e. half of the long term ground track spacing requirement of 8 km), a 0.006 m/s OTM would be required every 90 days. At the time of writing this paper, the minimum maneuver size had not been identified in the requirements. An OTM of 0.006 m/s may be too small to implement practically in which case the strategy could be to do larger maneuvers less often and have a larger ground track walk or perform a non-optimal maneuver by off-pointing the OTM direction resulting in an along-track component that would be the desired 0.006 m/s.

Both the desat and OTM strategies need further in-depth analysis in order to optimize fuel use and verify sufficient fuel is allocated in the mission Delta-V budget for the science phase. A navigation analysis is also needed to confirm baseline radiometric tracking and operational scenarios meet the requirements that would be necessary for planning desats and OTMs.

6.0 Collision Avoidance and Planetary Protection

The TGO altitude range of 371 km to 437 km would overlap with the Odyssey (ODY) orbit, the Mars Express (MEX) orbit, the planned MAVEN orbit, and possibly the orbit of the non-operational Mars Global Surveyor (MGS). In order to avoid possible collisions between spacecraft, it is recommended that the TGO project team work with the JPL Mars Program office and the JPL Mission Design and Navigation Section to assess risks, mitigations and operations impact.

The ODY orbit is frozen with an altitude range of 390 km to 454 km and a sun-synchronous inclination of 93.2 deg. The Mars Express orbit has a secular argument of periapsis, an altitude range of 315 km to 10,550 km, and an 86 deg inclination. The MAVEN orbit will have a similar inclination at 75 deg and an altitude range of 150 km to 6,220 km. The MGS mission ended in Nov 2006 most likely due to battery failure after lasting four times longer than originally planned. The current position of MGS is unknown but the spacecraft is likely to be within the altitude range of its final orbit (354 km by 410 km) at a sun-synchronous 92.9 deg inclination. The Mars Reconnaissance Orbiter (MRO) is at a lower altitude than TGO with an altitude range of 255 km to 320 km, a 92.6 deg inclination and frozen argument of periapsis; thus, should pose not threat of collision.

The lower TGO inclination of 74 deg would help reduce the collision risks. However, there would be two orbit-crossing points to consider every orbit for potential collisions. Figure 14 below shows the orbit altitude verses latitude plot for TGO as well as each of the operational spacecraft currently orbiting Mars along with the best estimate for MGS propagated out to the 2017-2019 time frame.

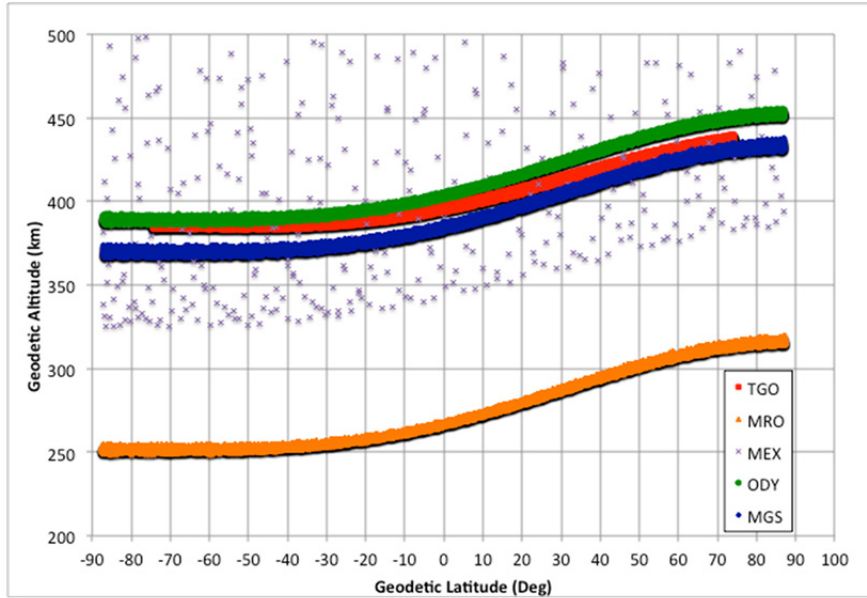


Figure 14: Orbit Altitude verses Latitude for TGO, ODY, MRO, and MEX from 2017-2019

At the time of writing this paper, there were no formal planetary protection requirements for TGO available from ESA. Compliance of orbit design and end of mission plans could not be verified. It is recommended that ESA plan the necessary resources to complete the planetary protection analysis when formal requirements are available.

7.0 Conclusion

The TGO science orbit design described above meets the needs for each of the original TGO science instrument teams. Due to the cancellation of NASA's participation on the TGO project, it is hoped that this orbit design can be used on a future mission to study the trace gases of Mars.

8.0 Acknowledgments

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9.0 References

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